

Wireless Sensor Networks

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Abstract—Directional antennas provide angle-of-arrival information, which can be used for localization and routing algorithms in wireless sensor networks. We briefly describe three classical, major types of antennas: 1) the Adcock-pair antenna, 2) the pseudo-Doppler antenna, and 3) the electronically switched parasitic element antenna. We have found the last type to be the most suitable for wireless sensor networks, and we present here the early design details and beam pattern measurements of a prototype antenna for the 2.4-GHz ISM band, the *SPIDA: SICS Parasitic Interference Directional Antenna*.

Keywords and phrases: Smart antenna, directional, direction finding, DF, RDF, wireless sensor network, localization, AOA, ESPE, ESPAR, parasitic element.

I. INTRODUCTION

Antennas for wireless sensor networks (WSN) need to satisfy a number additional of properties, besides those that are desired from all antennas, such as the antenna efficiency. Since there are many WSN nodes, *low cost* of the antenna is important. WSN nodes are *small*, which means antennas must also be small. The RF transceiver stage must be designed to *save power*, and *advanced signal processing capabilities cannot generally be expected*. However, for WSN, it is reasonable to assume that the antenna can be committed to narrow-band at one of the ISM-frequencies 434 MHz (wavelength $\lambda=69$ cm), 868 MHz ($\lambda=35$ cm) or 2.4 GHz ($\lambda=12.5$ cm).

In light of these considerations, we have compared three classical, major types of antennas that appear to be especially relevant candidates. These antenna types are 1) the Adcock-pair antenna, 2) the pseudo-Doppler antenna, and 3) the electronically switched parasitic element antenna. We will refer to these antenna types as the AP, PD, and ESPE antennas. We have found that the ESPE type is especially suitable for use in WSN. We have built and measured a prototype of such an antenna—*SPIDA*, for *SICS Parasitic Interference Directional Antenna*—and in this paper, we present the detailed design as well as some measurement results.

Radio direction finding (RDF) antennas can compute the angle of arrival (AOA) by measuring either the amplitude of the incoming signal, or the phase (or both). An advantage of measuring the phase is that it is less affected by noise, compared to amplitude. However, measuring

phase usually requires at least two input amplifiers and fast electronics with a highly stable timebase (cf. ultra-wideband, UWB). Since this is difficult to achieve for a WSN node, at least at the time of this writing, the main emphasis here is on methods using *amplitude* measurements.

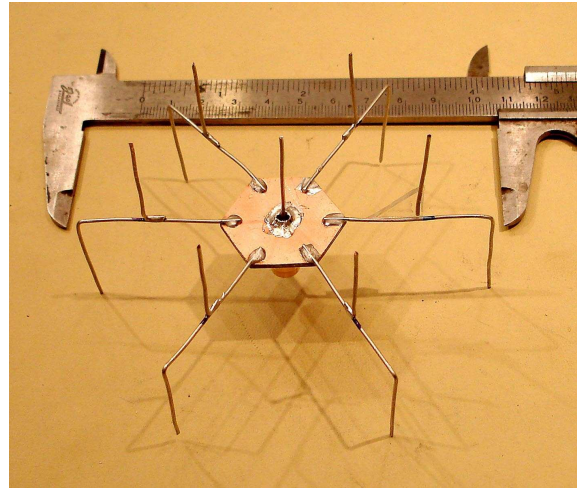


Fig. 1. SPIDA 2.44-GHz prototype.

II. RELATED WORK

Directional antennas have been intensively studied for many years, and all major relevant types of antennas appear to already have been invented several decades ago. Nevertheless, there is a flurry of suggestions in the literature on new types of small (i.e. diameter $< \lambda$) antennas. Despite this activity, the requirements imposed by WSN applications as described above are satisfied by surprisingly few classical designs. A thorough review of electrically small antennas, and a dismissal of most of them, is given in [12]. Considering the requirements above, three remaining potential candidate classes of antennas still feasible for WSN are described below.

A. The Adcock-pair Antenna

An *Adcock* antenna consists of a pair of parallel, vertical dipoles, spaced close together ($< \lambda/2$). The *difference* of the signal from the two antennas indicates the angle of arrival of an incoming signal. The lobe shape will be a

figure-of-eight, close to two circles if the dipoles are closely spaced. The *Adcock-pair* uses two Adcock antennas at a 90° angle. One pair gives the sine of the angle, while the other gives the cosine. This method was invented by Robert Watson-Watt, also the inventor of Radar, in the 1930s. It was invented as an improvement over loop antennas, frequently used for low-frequency radio direction finding (RDF) at that time.

The dipoles should *not* be tuned to the signal frequency, because the lobe shape is very sensitive to this tuning. Unfortunately, taking the difference of two closely spaced, non-tuned, parallel elements will make the antenna rather inefficient. It is also difficult to adjust the antenna, since the dipoles must have very similar properties. On the other hand, this method appears to produce the highest accuracy for direction finding. A good description of how to construct a simple AP antenna can be found in [1]. A thorough description of the Watson-Watt method for direction finding can be found in [4].

B. The Pseudo-Doppler Antenna

The PD antenna was invented by Servo Corporation in the 1940s. A PD antenna consists of a ring of dipole antennas spaced typically $\lambda/2$ apart. In turn, each dipole is switched to the input amplifier at a high frequency. This produces a sine wave at the RF receiver, and the phase of this wave will show the angle of arrival. A simple description with constructional details is available in [2].

The minimal number of active elements of a PD antenna is four, but it is usually used with 8 or 16 elements. Since the spacing is half a wavelength, the antenna becomes relatively large. However, due to the large aperture, the PD antenna is robust against noise. Detailed comparisons of PD and AP antennas can be found in [3] and [5].

C. The Electronically Switched Parasitic Element Antenna

The ESPE antenna consists of a central monopole, surrounded by a number of monopole-like parasitic elements spaced approximately $\lambda/4$ apart. In its simplest form, the parasitic elements are switched between ground, when they work as *reflectors*, and isolation, when they work as *directors*. In a more advanced form, the reactance between the elements is controlled. This can be done simply by biasing a capacitance diode with a controlled DC voltage.

The ESPE antenna principle appears to first have been published in 1979 [7]. This type of antenna has been discussed in detail in [6]. Recent work in this area has been performed by teams at ATR in Japan and at Griffith University in Australia [8, 9]. An interesting and attractive feature of the ESPE antenna is that the parasitic elements are not involved in the RF chain, greatly simplifying the impedance matching problem. The ring of parasitic elements on a ground plane can be added to a monopole, and each parasitic element can be controlled by a micro-

processor output. When implemented by an FET, such a switch will not consume any DC power.

In order to reduce the size of the antenna, the space between the elements can be filled with a dielectric. With a relative permittivity of ϵ_r , the theoretical size reduction of the antenna is $\sqrt{\epsilon_r}$. Descriptions of such antennas can be found in [8, 9]. Many practical pieces of information relevant for a 2.4 GHz antenna are given in [10]. Descriptions of ESPE antennas and an extensive bibliography is given in [11].

III. THE SPIDA DESIGN

SPIDA is a type of ESPE antenna, designed primarily for the 2.4 GHz ISM band. Distinguishing features are that SPIDA is simple and inexpensive to manufacture, consisting of a small circuit board and 1-mm copper wire; and that the beam pattern in the horizontal plane well approximates an offset circle, without any significant side-lobes, despite an 11-dB (7 dB effective) gain difference between 0° and 180° directions.

The SPIDA prototype consists of a small (≈ 3 cm in diameter) hexagonal disc made of copper-clad FR-4 circuit board, on which six legs made of 1-mm copper wire have been soldered (fig. 1). An SMA-connector is mounted centrally on the disc. A sensor network node can be attached directly to this connector, eliminating the need for a feed line.

The antenna was originally designed for the purpose of localization, implying that the antenna gain as a function of direction should ideally approximate the direction cosine. The simulation package Nec-2 [13] was extensively used for designing and optimizing the antenna with this target in mind. The 3D radiation pattern generated by Nec-2 is shown in figure 2.

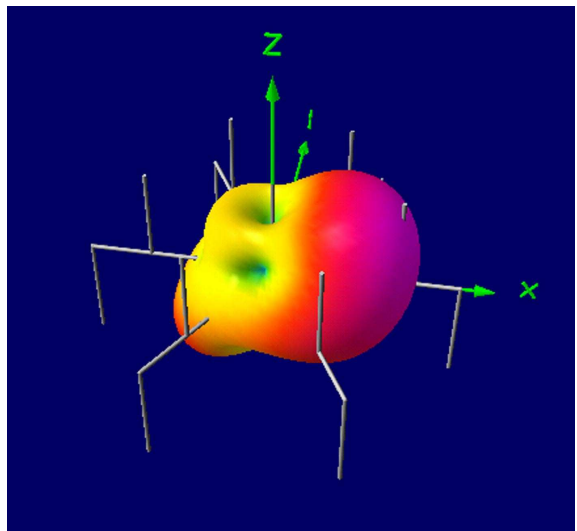


Fig. 2. Theoretical 3D gain pattern from Nec-2 simulation. The antenna is directed along the x-axis.

Here, both the distance from the origin and the shading indicates the gain in dB. An interesting observation in the process was that the smoothness of the radiation diagram in the horizontal plane could be improved by rather counter-intuitively reducing the size of the ground plane hexagonal disc.

The parts cost for SPIDA is marginal, and completely dominated by the SMA connector. The antenna can be built in a short time, and can be easily tuned, thanks to the radiation elements being ordinary copper wires, which can be bent and cut with good precision after soldering. The antenna does not require any additional amplifiers beyond those needed by an ordinary dipole. The parasitic elements can be switched at low frequency, without consuming DC power. This SPIDA prototype was built with the reflecting elements soldered to the ground legs, and the directing element permanently isolated (glued), but in an application, these elements would be connected to ground via electronic switches. Construction details are given in the appendix.

IV. MEASUREMENT RESULTS

The vertical gain in the horizontal plane for SPIDA has been measured both in simulation and in a damped measurement chamber. The ideal, smooth circular radiation diagram was well achieved in simulation (fig. 3).

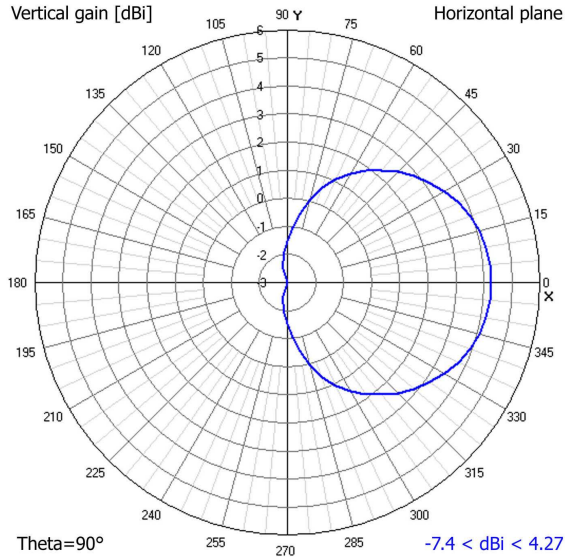


Fig. 3. The SPIDA horizontal beam pattern approximates an offset circle (from simulation).

This also agreed reasonably well with the physical measurements (fig. 4).

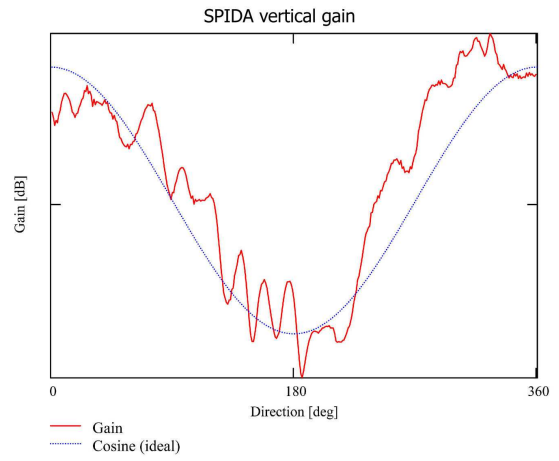


Fig. 4. SPIDA horizontal radiation pattern as measured in measurement chamber.

V. CONCLUSIONS

We have reviewed plausible candidates for directional antennas that can be used by WSN nodes. Due to its simplicity and low cost, the proposed SPIDA instance of the ESPE antenna structure appears to be an attractive candidate. The special structure of SPIDA produces a beam pattern well suited to efficient signal processing. However, the quality of measurements (i.e. RMS error in angular measurements) is also an important consideration, which is hard to predict theoretically. In order to investigate this, antennas will have to be tested in their intended environments.

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VIII. APPENDIX: SPIDA DRAWING

Figure 5 shows a drawing of the 2.44-GHz prototype of SPIDA. The board can be made from standard copper laminate. Double-sided is practical, but not necessary. Wires are 1-mm copper wire. It is a good idea to make legs a little longer, and then bend and cut to length after everything has been soldered. The hole in the middle is intended for an SMA male-to-coaxial connector. The monopole is mounted as the central lead. All parasitic elements (27mm) are ground, except one, which should be isolated (glued).

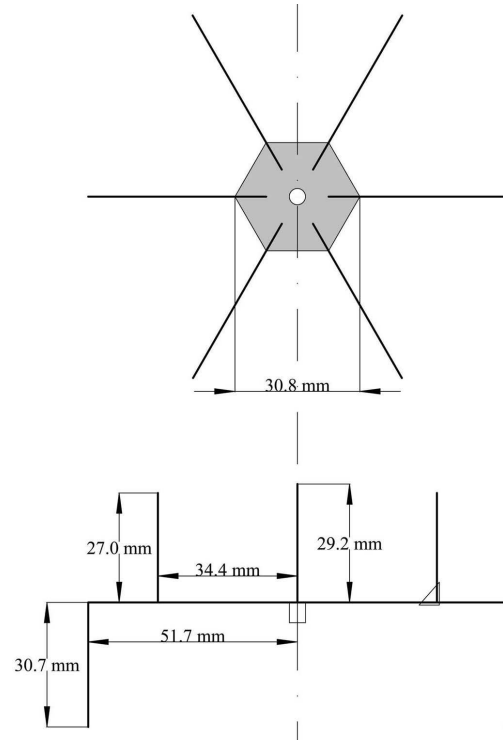


Fig. 5. SPIDA 2.44-GHz prototype dimensions.